NACA L-82

CB No. L5J04

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

November 1945 as
Confidential Bulletin L5J04

EFFECTS OF REYNOLDS NUMBER AND LEADING-EDGE ROUGHNESS ON LIFT AND DRAG CHARACTERISTICS OF THE NACA 65_3-418, a = 1.0 AIRFOIL SECTION

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CONFIDENTIAL BULLETIN

EFFECTS OF REYNOLDS NUMBER AND LEADING-EDGE ROUGHNESS ON LIFT AND DRAG CHARACTERISTICS OF THE NACA 65_3-418, a = 1.0 AIRFOIL SECTION

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SUMMARY

Tests were made in the Langley two-dimensional low-turbulence tunnels of an NACA 65_3-418, a = 1.0 airfoil section with roughness in the form of carborundum grains applied to the leading edge. Roughness grains having average diameters of 0.0003 and 0.0007 airfoil chord were applied to the leading edge of the wing, and lift and drag measurements were made for a range of Reynolds numbers from 0.23 to 3.0×10^6. From a comparison of data obtained in the present tests with data obtained in tests of the smooth wing, marked reductions in maximum lift coefficient were found to be caused by the roughness throughout the test range of Reynolds number. The drag coefficient at the design lift coefficient increased sharply and the lift-curve slope decreased rapidly at a critical Reynolds number that depended upon the size of the carborundum grains. This critical Reynolds number occurred at approximately 0.50 and 0.70×10^6 for the 0.0003- and the 0.0007-chord-diameter roughness grains, respectively. With roughness, a decrease in maximum lift coefficient as great as 0.2, a decrease in lift-curve slope of 0.028, and an increase in drag coefficient at the design lift coefficient of 0.007 were observed at a Reynolds number of 1.0×10^6. For the smooth wing at the same Reynolds number, the maximum lift coefficient was 1.19, the lift-curve slope was 0.116, and the drag coefficient was 0.0077. At Reynolds numbers greater than 1.0×10^6, the scale effect on the lift and drag characteristics of the section with both degrees of roughness was generally in the same direction as the effect on the lift and drag characteristics of the smooth airfoil.

INTRODUCTION

Several investigations have been made in the past to determine the effects of Reynolds number on the aerodynamic characteristics of various airfoil sections. A recent investigation was made (reference 1) to determine the effects of both Reynolds number and stream turbulence on the lift and drag of a smooth NACA 6-series airfoil section.

The present investigation was made to determine the effects of Reynolds number on the lift and drag characteristics of an NACA 6-series section with a roughened leading edge. Tests were made, therefore, of the NACA 65_3-418, a = 1.0 airfoil section in the Langley two-dimensional low-turbulence tunnels over a range of Reynolds number from 0.23 to 3.0×10^6. Lift and drag measurements were made at several Reynolds numbers in this range with two degrees of roughness applied to the leading edge of the airfoil.

Although the data presented herein and in reference 1 are quantitatively correct only for the NACA 65_3-418 airfoil section, the effects of Reynolds number and roughness would probably be in the same general direction and of approximately the same order of magnitude for other NACA 65-series airfoil sections that do not differ greatly in thickness and camber from the NACA 65_3-418. These results are also helpful in properly evaluating the merits of low-scale test data.

SYMBOLS

c_l	section lift coefficient
c_d	section drag coefficient
c_{l_i}	design section lift coefficient
$c_{l_{max}}$	maximum section lift coefficient
c	airfoil chord

R	Reynolds number
α_0	section angle of attack

MODELS AND TEST METHODS

The airfoil model used in the present investigation was of 6-inch chord and was constructed of aluminum alloy to correspond to the ordinates of the NACA 65_3-418, a = 1.0 airfoil section. Ordinates for this airfoil section are presented in reference 2. A photograph of the model is presented in figure 1.

Roughness was simulated by applying carborundum grains of a given diameter to the leading edge of the wing with shellac. The roughness was applied to both surfaces of the airfoil as far back as 0.078c and the grains covered approximately 10 percent of the roughened area. Two degrees of roughness were obtained by use of grains having average diameters of 0.0003c (0.002 in.) and 0.0007c (0.003 to 0.005 in.). The standard roughness used in systematic airfoil investigations (reference 2) for determining the characteristics of various airfoils having transition fixed at the nose is composed of grains having average diameters of 0.0005c. This standard roughness was thought to be considerably more severe than that caused by any manufacturing irregularities or poor painting precedures but is not so severe as that caused by icing, mud, or damage from military combat. One grain roughness used in the present tests is larger than the standard roughness; the other is smaller.

The tests were made in the Langley two-dimensional low-turbulence tunnel (designated LTT) and in the Langley two-dimensional low-turbulence pressure tunnel (designated TDT). Both tunnels are 3 feet wide and $7\frac{1}{2}$ feet high and were designed to test models completely spanning the jet in two-dimensional flow. These tunnels are characterized by air streams having exceptionally low turbulence levels, of the order of a few hundredths of 1 percent. Lift measurements were made by an arrangement designed to integrate the pressure reactions along the floor and ceiling of the tunnel test sections and drags were measured by the wake-survey method.

All tests were run at tunnel Mach numbers less than 0.2. Measurements were made at atmospheric pressure in the LTT, and at tunnel pressures of 14.7, 30, 45, 63, and 87 pounds per square inch absolute in the TDT.

Corrections for the effects of tunnel-wall interference and air-stream constriction were applied to the model as follows:

$$c_l = 0.998\ c_l'$$

$$c_d = 0.999\ c_d'$$

where the primed quantities represent the values obtained in the tunnel.

RESULTS AND DISCUSSION

Lift characteristics for the NACA 65_3-418, a = 1.0 airfoil section at various Reynolds numbers with two degrees of leading-edge roughness are presented in figure 2 and the drag characteristics are presented in figure 3. In figure 2(a), in which data are presented for the model having 0.0003c-diameter grains on the leading edge, a pronounced jog in the lift curve is noticeable at a lift coefficient of 0.9 at a Reynolds number of 0.50×10^6. In reference 3 such a jog was found to be associated with a region of laminar separation just behind the leading edge of the wing. The fact that a jog occurred in the present tests indicates that this degree of roughness did not completely eliminate laminar flow at the leading edge until a Reynolds number between 0.50 and 0.75×10^6 was attained.

From figures 2(b) and 2(c), in which data are presented for the model having 0.0007c-diameter grains on the leading edge, no jog occurred in the lift curve at Reynolds numbers greater than 0.35×10^6. This degree of roughness therefore probably eliminated laminar flow entirely at a Reynolds number between 0.35 and 0.50×10^6.

Curves showing the variation of maximum lift coefficient and lift-curve slope with Reynolds number are presented in figure 4 and the variation of drag coefficient at the design lift coefficient with Reynolds number, in figure 5. Application of roughness to the leading edge of the airfoil caused values of the maximum lift coefficient and the lift-curve slope that were substantially lower than the values for the smooth airfoil (fig. 4). The maximum lift coefficients and the lift-curve slopes are predominantly lower than those for the smooth wing throughout the test range of Reynolds number, and there is a critical Reynolds number at which the maximum lift coefficient decreases noticeably and the lift-curve slope decreases rapidly. Figure 5 shows that at this critical Reynolds number a sharp increase in the variation of the drag coefficient at the design lift coefficient with Reynolds number also occurred. The lift-curve slope decreases rapidly and the drag coefficient at the design lift coefficient increases sharply at a Reynolds number of approximately 0.70×10^6 for the 0.0003c-diameter grain roughness and of approximately 0.50×10^6 for the 0.0007c-diameter grain roughness. At a Reynolds number of 1.0×10^6, however, the differences in values of the lift-curve slope and of the drag coefficient for the two degrees of roughness disappear, and at greater Reynolds numbers, within the accuracy of the results, the values of these quantities appear to be independent of the sizes of the roughness for which data are presented.

The lift-curve slopes in figure 4 also show that for the 0.0003c-diameter grain roughness the lift-curve slope is essentially the same as for the smooth wing up to a Reynolds number of at least 0.50×10^6. This degree of roughness probably brought about no significant changes at low lift coefficients in the development of the boundary layer from that existing on the smooth wing up to a Reynolds number of 0.50×10^6. Because the maximum lift coefficient for this degree of roughness was lower than that for the smooth wing throughout the entire range of test Reynolds numbers, the roughness probably did induce some change in the nature of the flow at high lift coefficients.

With the 0.0007c-diameter roughness grains, the lift-curve slope and maximum lift coefficient were greater than those of the smooth wing at a Reynolds number of 0.25×10^6, but at Reynolds numbers greater than 0.30×10^6 these quantities were lower than those of the smooth airfoil for both degrees of roughness. The reason for this phenomenon is not readily evident. There is a possibility, however, that at a Reynolds number of 0.25×10^6 the roughness was not large enough to destroy the laminar flow entirely but was large enough to prevent laminar separation behind the minimum pressure point. A boundary-layer velocity distribution would result, therefore, which would be different from both the smooth flow condition and the smaller roughness condition.

Figure 4 shows that at Reynolds numbers between 1.0 and 3.0×10^6 the maximum lift coefficients were less than those of the smooth wing by approximately 0.14 and 0.20 for the 0.0003c- and 0.0007c-diameter roughness grains, respectively. At a Reynolds number of 1.0×10^6, the lift-curve slope of the rough wings was 24 percent less than that of the smooth wing, but at a Reynolds number of 3.0×10^6, a decrease due to roughness of approximately 12 percent in lift-curve slope was found. A constant increment in drag coefficient at the design lift coefficient due to roughness of approximately 100 percent was found (fig. 5) at Reynolds numbers between 1.0 and 3.0×10^6.

CONCLUSIONS

A comparison of results of tests of the NACA 65_3-418, a = 1.0 airfoil section for a range of Reynolds number from 0.23 to 3.0×10^6 with roughness grains having average diameters of 0.0003 and 0.0007 airfoil chord (0.0003c and 0.0007c) with results of previous tests of the smooth wing led to the following conclusions:

1. Maximum lift coefficients of the airfoil with roughness were generally lower than those obtained on the smooth airfoil section throughout the test Reynolds number range. At a Reynolds number of 1.0×10^6 the maximum lift coefficient for the smooth wing was reduced from a value of 1.19 to 1.05 and 0.99 by the 0.0003c- and 0.0007c-diameter grains, respectively.

2. There is a critical Reynolds number at which the lift-curve slope decreases rapidly and the drag coefficient increases sharply depending upon the size of the roughness. This critical Reynolds number was approximately 0.70 and 0.50×10^6 for the 0.0003c- and 0.0007c-diameter grains, respectively.

3. With roughness, at a Reynolds number of 1.0×10^6, the lift-curve slope was 0.088 and the drag coefficient at the design lift coefficient was 0.0155 whereas the

corresponding values for the smooth airfoil section were 0.116 and 0.0077, respectively. At Reynolds numbers greater than 1.0×10^6 the changes in lift-curve slope and drag coefficient were nearly independent of the sizes of the roughness for the two degrees of roughness for which the effects were measured.

4. Large variations in the lift and drag characteristics of the airfoil were found in the range of Reynolds number between 0.23 and 1.0×10^6. At Reynolds numbers greater than 1.0×10^6, the scale effect on the lift and drag characteristics of the section with both degrees of roughness was generally in the same direction as the scale effect on the characteristics of the smooth airfoil.

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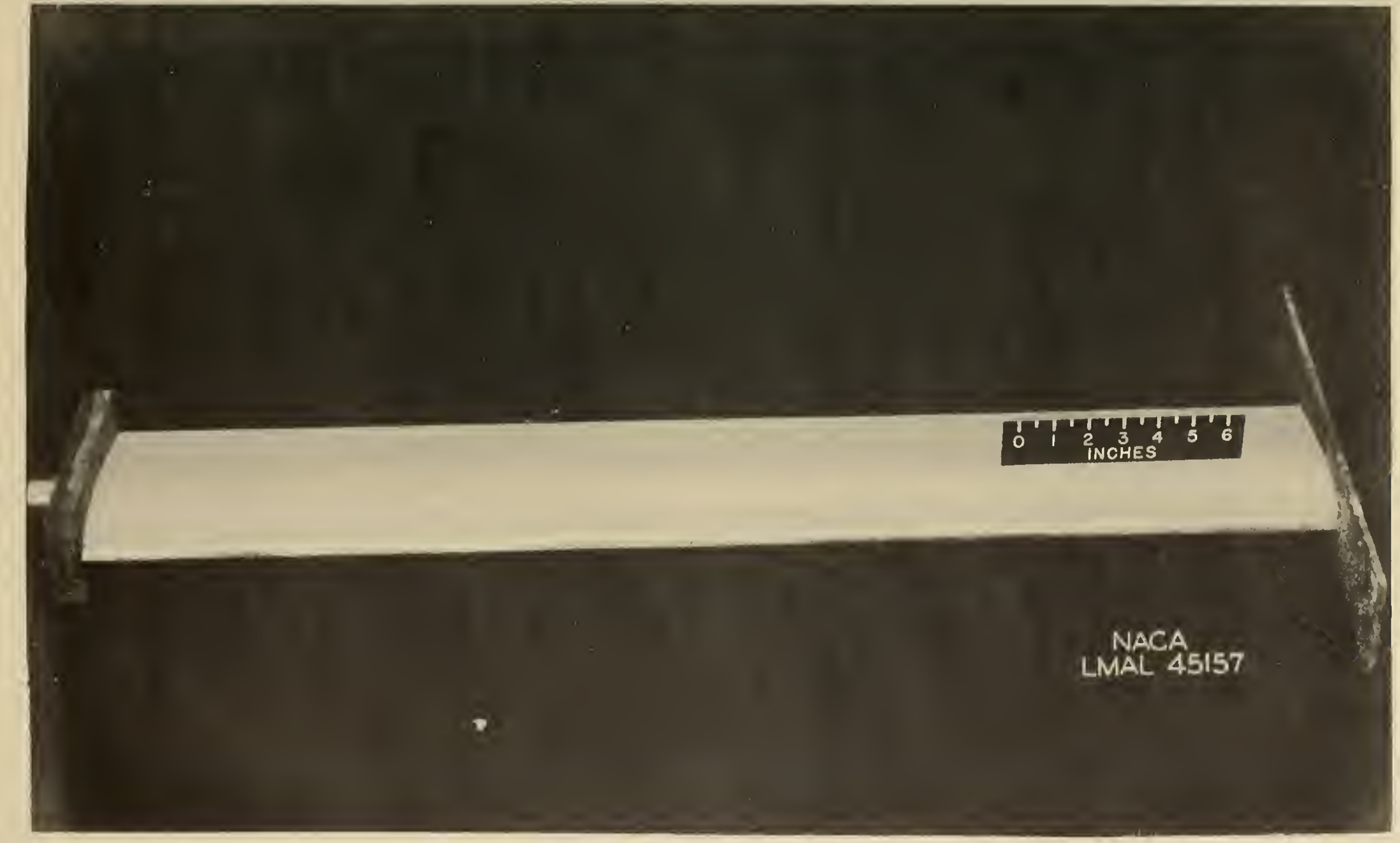

Figure 1.- Photograph of NACA 65_3-418, a = 1.0 airfoil section with 0.0007c-diameter roughness grains applied to leading edge.

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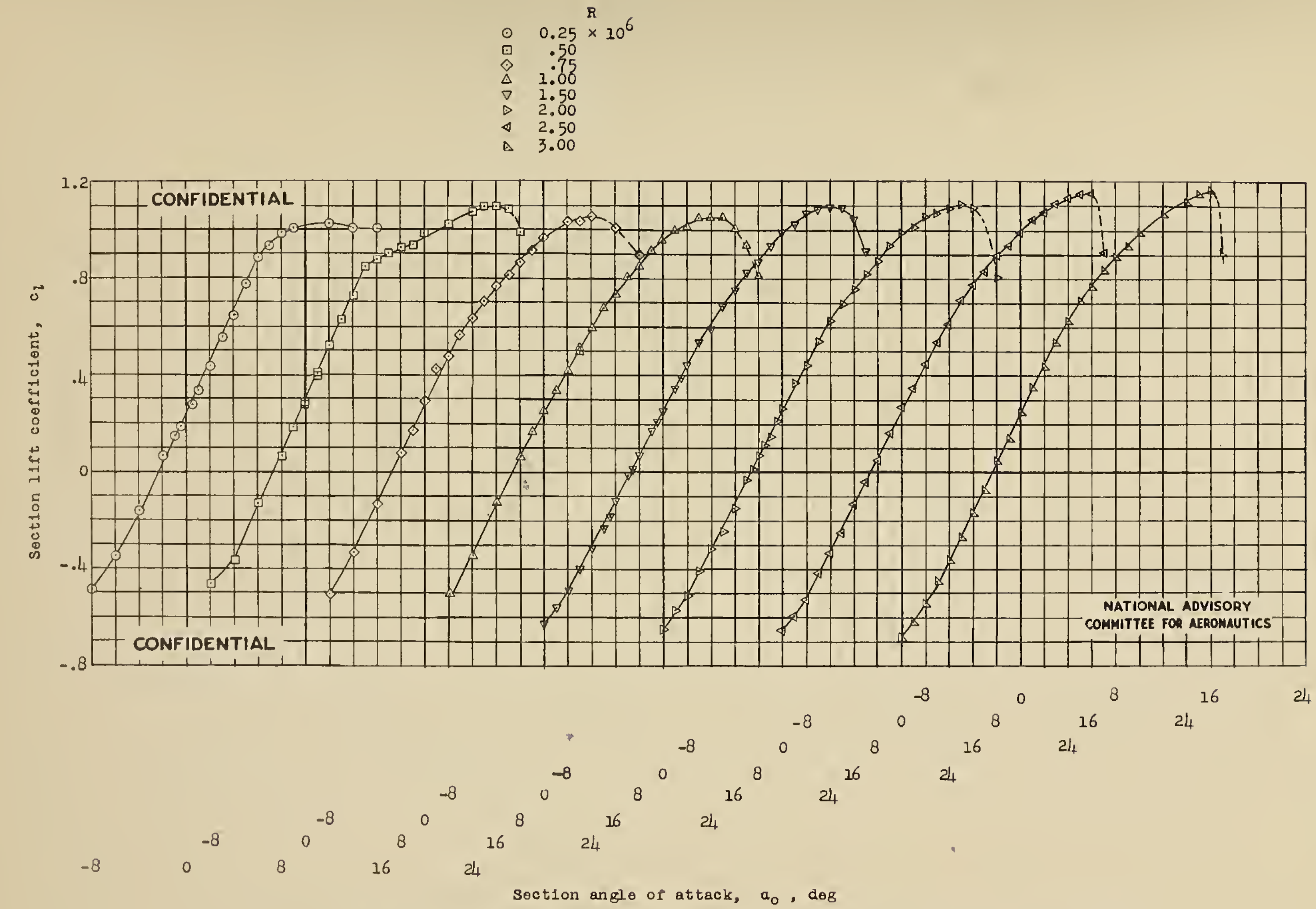

(a) Model in TDT having 0.0003c-diameter grains applied to leading edge. TDT test 867.

Figure 2.- Variation of section lift coefficient c_l with angle of attack α_o for the NACA 65_3-418 airfoil section having two degrees of leading-edge roughness. Model chord, 6 inches.

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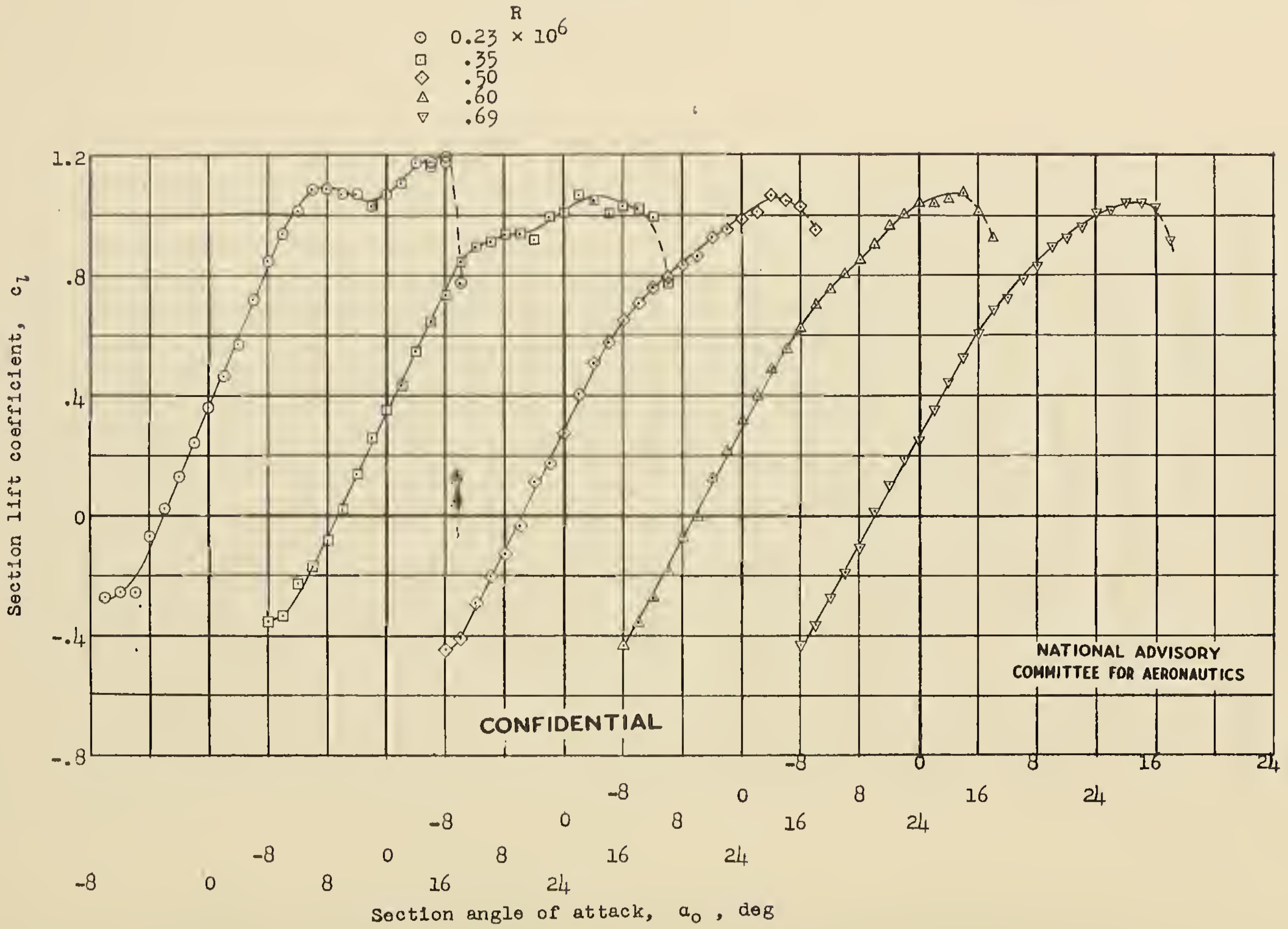
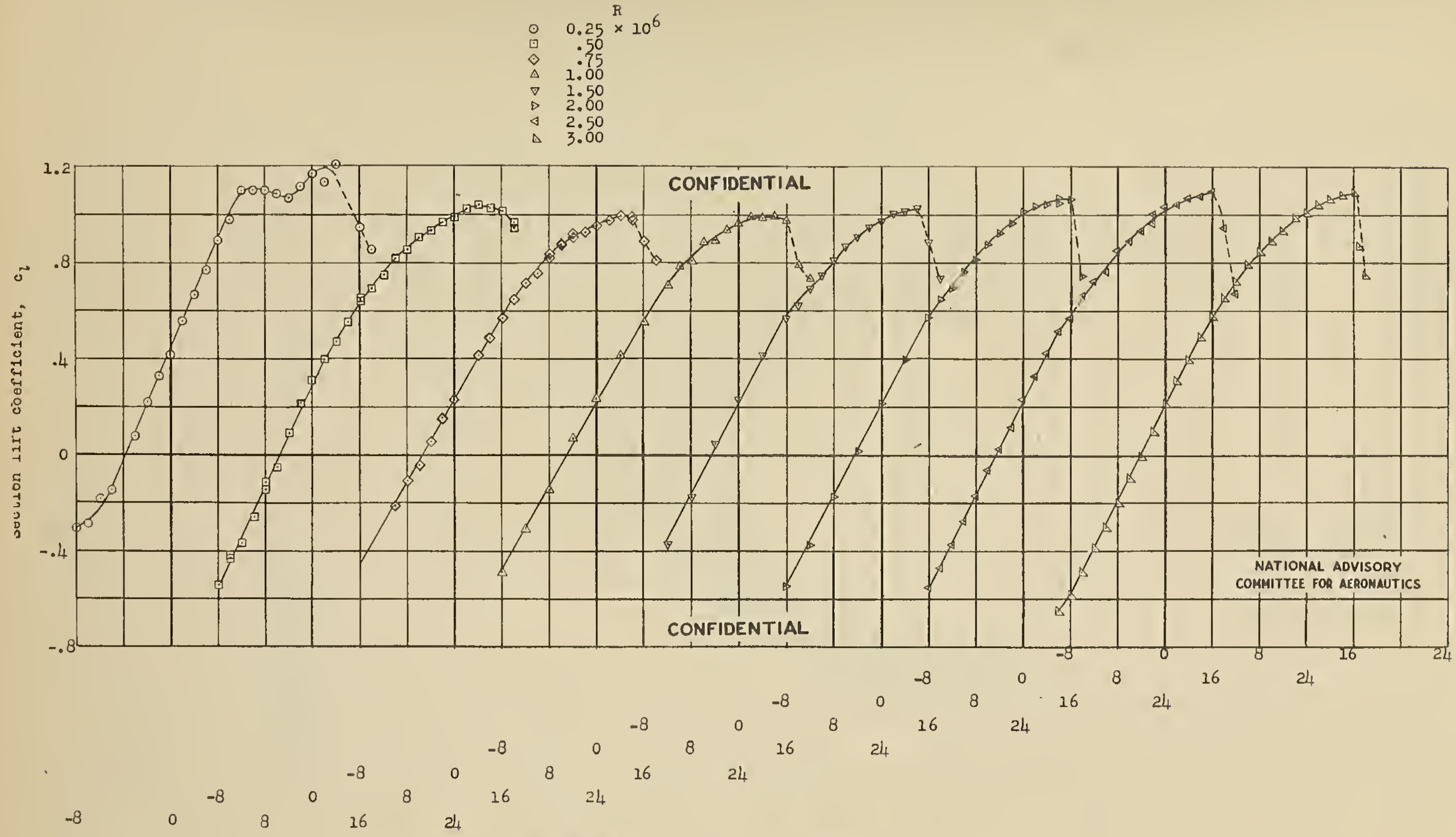


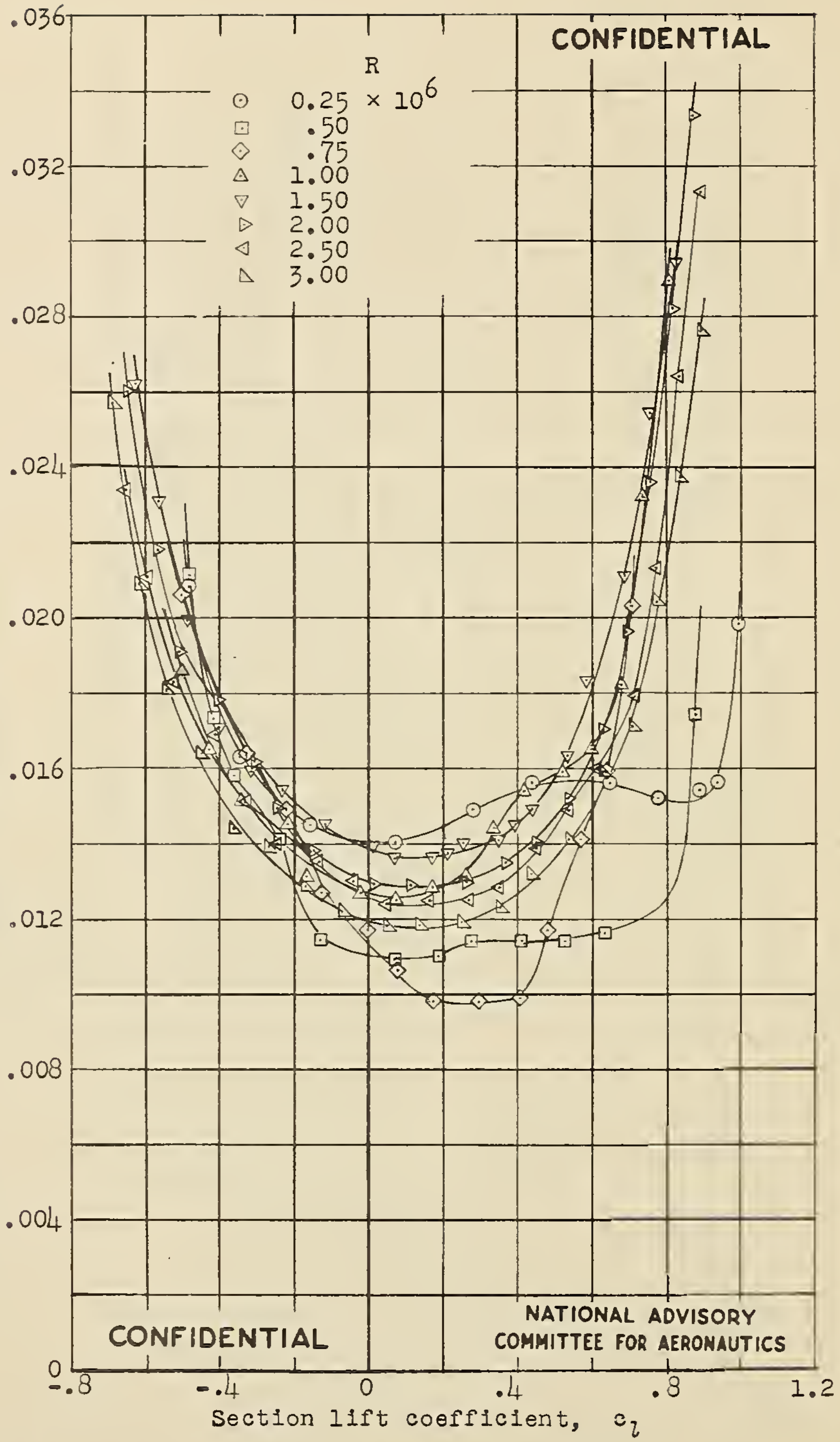
(b) Model in LTT having 0.0007c-diameter grains applied to leading edge. LTT test 404.

Figure 2.- Continued.



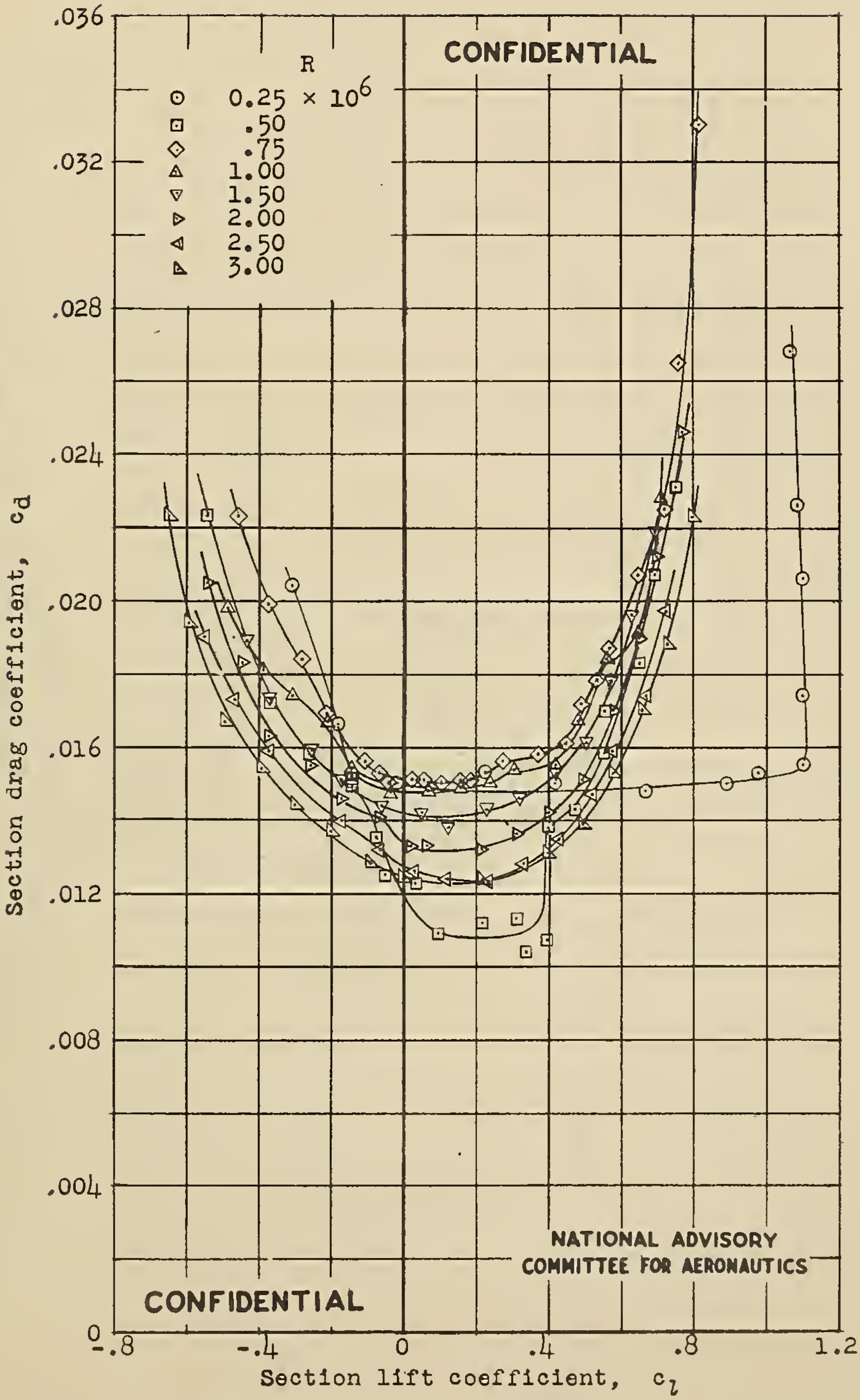
(c) Model in TDT having 0.0007c-diameter grains applied to leading edge.
TDT test 873.

Figure 2.- Concluded.



(a) Model having 0.0003c-diameter grains applied to leading edge. TDT test 867.

Figure 3.- Variation of section drag coefficient c_d with section lift coefficient c_l for the NACA 65_3-418 airfoil section having two degrees of leading-edge roughness. Model chord, 6 inches.



(b) Model having 0.0007c-diameter grains applied to leading edge. TDT test 873.

Figure 3.- Concluded.

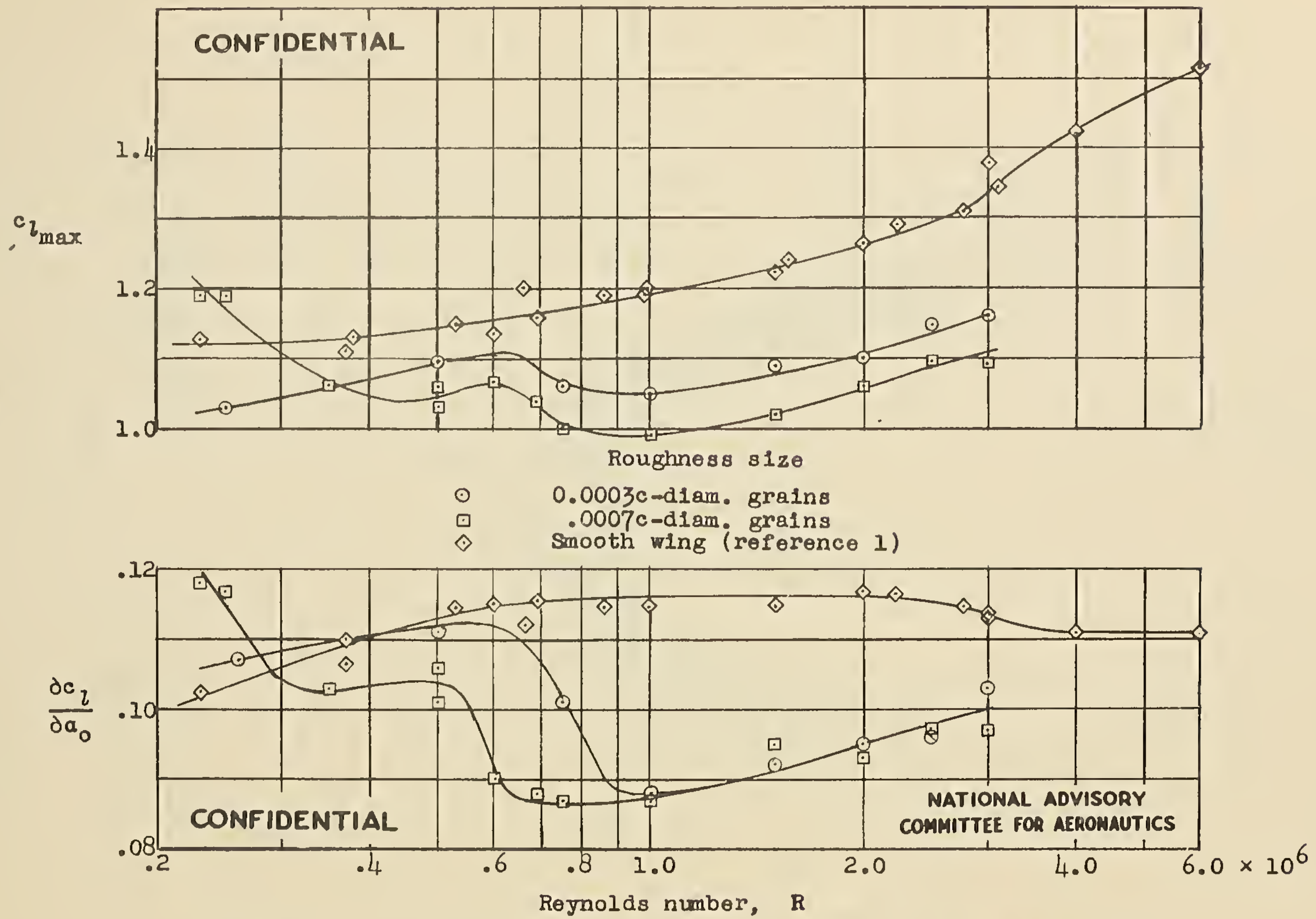


Figure 4.- Variation of lift-curve slope $\frac{\partial c_l}{\partial \alpha_o}$ and maximum section lift coefficient $c_{l_{max}}$ with Reynolds number for the NACA 65_3-418 airfoil section having various degrees of leading-edge roughness.

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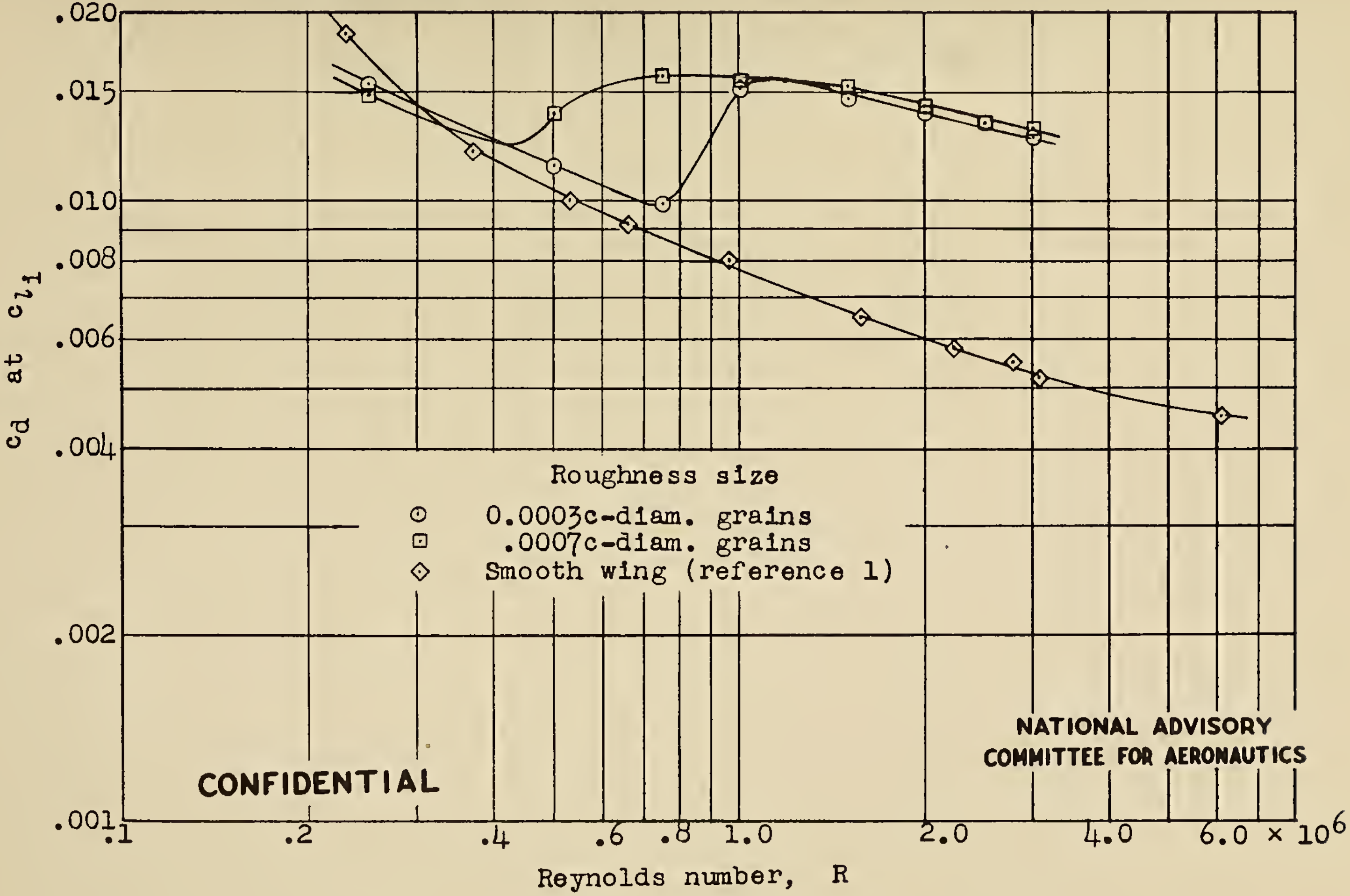

Figure 5.- Variation of section drag coefficient c_d at design section lift coefficient c_{l_i} with Reynolds number for the NACA 65_3-418 airfoil section having various degrees of leading-edge roughness.

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